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Sensor Based Engine Life Calculation—A Probabilistic Perspective

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Abstract

It is generally known that an engine component will accumulate damage (life usage) during its lifetime of use in a harsh operating environment. The commonly used cycle count for engine component usage monitoring has an inherent range of uncertainty which can be overly costly or potentially less safe from an operational standpoint. With the advance of computer technology, engine operation modeling, and the understanding of damage accumulation physics, it is possible (and desirable) to use the available sensor information to make a more accurate assessment of engine component usage. This paper describes a probabilistic approach to quantify the effects of engine operating parameter uncertainties on the thermomechanical fatigue (TMF) life of a selected engine part. A closed-loop engine simulation with a TMF life model is used to calculate the life consumption of different mission cycles. A Monte Carlo simulation approach is used to generate the statistical life usage profile for different operating assumptions. The probabilities of failure of different operating conditions are compared to illustrate the importance of the engine component life calculation using sensor information. The results of this study clearly show that a sensor-based life cycle calculation can greatly reduce the risk of component failure as well as extend on-wing component life by avoiding unnecessary maintenance actions.

Nomenclature

D	True Ductility
$\Delta\varepsilon_t$	Total Strain Range
$\Delta\varepsilon_{el}$	Elastic Strain Range
$\Delta\varepsilon_{pl}$	Plastic Strain Range
$\Delta T_{\max}$	Max. Temperature Different between the airfoil and the endwall
E	Modulus of Elasticity
F	Probability of Failure
ITT	Inter Turbine Temperature
LCF	Low Cycle Fatigue
N_c	Safe Life Cycles
N_{cum}	Cumulative Cycles
N_f	Cycles-to-failure (Designed)
N_f*	Cycles-to-failure (Computed)
N_{eq}	Equivalent Cycle
N_{min}	Minimum Critical Damage Cycles
N_w	Weibull Slope Number
NH	High Pressure Turbine Speed
NL	Low Pressure Turbine Speed
PLA	Power Lever Angle
σ_{UTS}	Ultimate Tensile Strength
S.D.	Standard Deviation
T3	Compressor Discharge Temperature
T4	Turbine Inlet Temperature
T_{m}	Metal Temperature of Airfoil
TMF	Thermomechanical Fatigue

Introduction

Turbine engine life management is a very complicated process used to ensure the safe operation of an engine subjected to complex usage. The challenge of life management is to find a reasonable compromise between safe operation and maximum usage of critical parts to reduce operating costs. In the certification process of an engine, all failure modes of critical engine parts are analyzed by advanced tools including finite element analysis and extensive material testing. Once these failure modes are established, the analysis typically uses a standard operating mission cycle to find the maximum damage of a component. This value is then used to determine the maximum allowable cycle count the part may incur before it requires maintenance which is referred to as the "safe life." This approach is particularly useful for low cycle fatigue (LCF) damage and thermomechanical fatigue (TMF) damage as these types of damage accumulate nominally only once every flight [1,2]. After

certification, the approach used for life usage calculation of many engine components is based on simple take-off/landing cycle counts regardless of the operating conditions of the engine. This commonly used "cycle count" approach does not take engine operating conditions into account and overly simplifies the calculation of life usage. Because of these shortcomings in the life calculation approach, many engine components are regularly pulled for maintenance before their usable life is fully consumed. And, in other cases, if an engine has been regularly operating under more severe conditions, it may pose a risk by remaining in service after its true "safe life" has been consumed.

In this study, the TMF damage to a cooled turbine stator is selected to demonstrate the impact of operating parameter uncertainties on life calculation and corresponding probability of failure. First, the TMF life model of an engine component is examined. A Weibull distribution is then used to estimate the implied probability of failure for a given accumulated cycle count [3,6]. A closed-loop engine model is developed to simulate engine operation across the mission profile. A simplified TMF damage model is used to calculate the actual damage during take-off where maximum TMF accumulates. Monte Carlo simulations are then employed to generate profiles of TMF damage under different operating assumptions including parameter uncertainties. Probabilities of failure for different operating conditions are analyzed to demonstrate the benefits of a sensor-based damage calculation in order to better manage component risk of failure and on-wing life.

TMF Life Model

A gas turbine engine consists of various components. These components are subject to different types of thermomechanical damage. Specifically, many critical components in the engine hot-section (i.e. the combustor and the high pressure turbine sections) experience an accelerated rate of damage. Although there are many failure modes in the operation of engines, for the purposes of this study we will only focus on the cumulative fatigue damage for hot-section components where the conventional method of calculating component life usage is primarily based upon the use of simple cycle counts. Damage is accumulated while an engine is in service. Therefore, it is highly desirable to have the ability to accurately track the amount of damage accumulation, and to have the ability to control the engine in a manner to avoid excessive damage [4,7].

Thermomechanical fatigue (TMF) damage is the complex repeated to-and-fro motion of atomic dislocations that interact with time-dependent thermally activated creep and oxidation mechanisms. Once a sufficient amount of inelastic strain induced disruption to the crystalline lattice has been accumulated, the material cannot sustain additional inelastic strain without initiating microcracks. The time taken to arrive at this condition is a function of the applied strain, material properties, operating temperature, and the number of repetitions. These microcracks then act as sites for crack propagation to begin [5].

The cycles-to-failure, N_f, of an engine component is represented by a number of standard operating cycles that will accumulate enough damage for component failure (i.e. crack initiation in many cases). The safe life limit, N_c, is usually selected as a fraction of the calculated number of cycles-to-failure, N_f, according to the criticality of the component. In this study, we will use the TMF model of a cooled turbine stator (of a commercial engine) to illustrate the relationship between component probability of failure and the variation of operating parameters which the component may experience.

The relationship between the cycles-to-failure, N_f, and the total mechanical strain range, $\Delta\varepsilon_t$, for TMF is usually described by an equation of the form [1]:

$$\Delta\varepsilon_t = \Delta\varepsilon_{el} + \Delta\varepsilon_{pl} = A\left(N_f\right)^{\alpha} + B\left(N_f\right)^{\beta} \qquad (1)$$

Where $\Delta\varepsilon_{el}$ and $\Delta\varepsilon_{pl}$ are the elastic and plastic strain ranges. Typically, the coefficients A and B are time- and temperature-dependent due to creep and oxidation mechanisms. They may also depend on the phasing between thermal and mechanical loading. For our current demonstration purposes, however, we will approximate the TMF resistance by using the simpler, but well-known, isothermal "Method of Universal Slopes (MUS)" equation [2,5]:

$$\Delta\varepsilon_t = 3.5(\sigma_{UTS}/E)(N_f)^{-0.12} + D^{0.6}(N_f)^{-0.6} \qquad (2)$$

Note that total strain range, σ_{UTS}, modulus of elasticity, E, and true ductility, D are all functions of operating temperature. Equation (2) is usually plotted as a family of isothermal curves for

different metal operating temperatures. The total strain range, $\Delta\varepsilon_t$, is determined by the engine operating parameters (such as gas temperature, metal temperature, cooling flows) during the flight. N_f is determined from the isothermal curve of the corresponding operating temperature. In selecting the "safe life" of a component, the "10% Rule" is a commonly used practice. It simply sets the limit of component operation at one tenth of N_f [2].

Figure 1 shows a total-strain-range vs. cycles-to-failure curve from equation (2) and a safe life curve set by the "10% Rule". The figure also shows an example of a given total-strain-range of approximately 0.022, N_f is calculated as 50,000 standard take-off/landing missions, and the safe life limit, N_c, is selected as 5,000.

While N_f depends on the material properties as well as the operating conditions, it is more convenient to set N_f as a constant for a standardized condition and adjust the cycle count, n, for actual operating conditions.

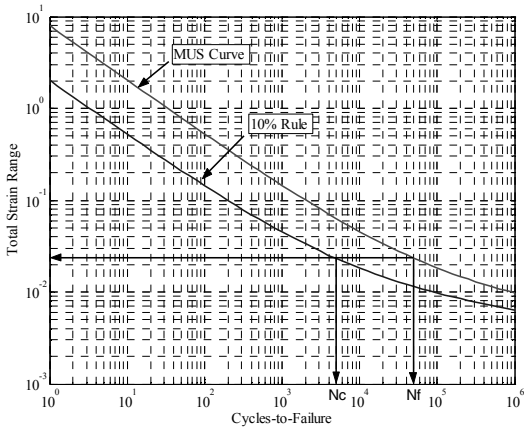

Figure 1. Cycles-to-Failure Curve and 10% Rule

Probability of Failure

In order to make a comparison between different operating scenarios, it is necessary to set a standard calculation for the component "probability of failure." In this paper we will assume that the probability of failure of an engine component due to thermomechanical fatigue (TMF) can be approximated by a three-parameter Weibull distribution based on cumulative effective cycle count [3,6]. The Weibull distribution is a simple yet powerful tool that can provide a generalized probability function using the following equation:

$$F = 1 - \exp\left[-\left(\frac{N_{cum} - N_{\min}}{N_f - N_{\min}}\right)^{N_W}\right] \qquad (3)$$

Where F represents the probability of failure; N_{min} is the Weibull location parameter for minimum damage threshold, and N_f represents nominal cycles-to-failure counts; and N_{cum} is a variable representing cumulative damage count. Figure 2 shows the probability of failure model using a three parameter Weibull distribution, where the Weibull slope number, N_w, is 4; N_{min} is 0; and, N_f is 50,000. Again, a typical life limit is set to have the engine serviced at one tenth of the nominal cycles-to-failure, N_f. Using the above assumptions, the baseline probability of failure can be calculated based on the design TMF life usage model over 5,000 flights at nominal operating conditions. This selection implies a 0.01% probability of component failure when the engine is operated under nominal condition for 5,000 flights.

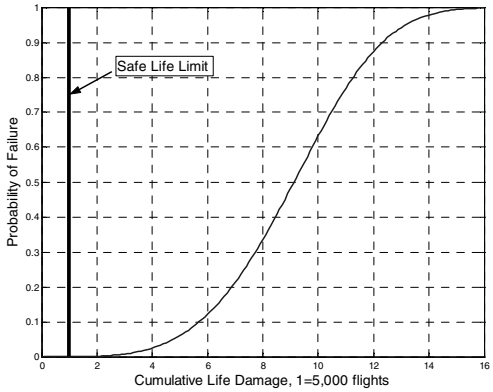

Figure 2. Weibull Distribution for Probability of Failure

Engine Simulation and Cycle Count

In order to study the effects of varying (off-nominal) engine operating conditions on component damage accumulation, a closed-loop simulation of an in-service commercial gas turbine engine was constructed in the Matlab/Simulink™ environment. This simulation consists of a piece-wise linear model of the engine and the embedded C code of a digital engine controller. The turbine first stage cooled stator of the selected engine has a design safe life of 5,000 take-off/landing cycles at nominal operating conditions. This design safe life will be used throughout this paper as the reference point for study purpose. A simplified damage model (described below) that matches the

design life of the turbine first stage cooled stator is also included in the simulation.

Since total strain range, $\Delta\varepsilon_t$, is not easily assessable during engine operation, it is desirable to represent the cycles-to-failure, N_f, as a function of engine operating parameters which are available from sensors or an on-board model. These parameters include core gas temperature, cooling air temperature, and metal temperature. If the engine is operated within a small range of temperatures, it is possible to simplify the calculation of N_f* of a specific flight cycle as a non-linear function in the following equation [4]:

$$N_f^* = f(\Delta T_{\max}, T_m) \tag{4}$$

where $\Delta T_{\max}$ is the maximum temperature difference between the airfoil and the endwall during one flight cycle, and T_m is the metal temperature when the maximum temperature difference occurs. Once the cycles-to-failure value, N_f*, is determined, an equivalent damage count, N_{eq}, can be calculated by taking the fraction of life usage and normalizing to the standard operation cycle count number.

$$N_{eq} = \left[\left(\frac{1}{N_f^*}\right) \Big/ \left(\frac{1}{N_f}\right) \right] = \left(\frac{N_f}{N_f^*}\right) \tag{5}$$

The SIMULINK™ block diagram of this simulation model is shown in Figure 3 [4]. The external inputs to the system are Altitude, Mach number, and Power Lever Angle (PLA). The Electronic Control Unit (ECU) block is built based on the embedded digital electronic engine controller of the selected engine. In this model, the controller module determines the fuel flow rate based on Altitude, Mach number, PLA, P3 (compressor discharge pressure), ITT (inter turbine temperature, NH (high pressure turbine speed), and NL (low pressure turbine speed). The Engine Model Block is a piece-wise linear model developed to match the non-linear simulation of an engine over a wide range of operation. The inputs to the piece-wise linear model of the engine are altitude, Mach number, and fuel flow rate (Wf). The outputs of the engine module are P3, T3 (compressor discharge temperature), T4 (turbine inlet temperature), ITT, NH, and NL. Here, P3, T3, ITT, NH, and NL are simulating the actual sensor outputs of an engine. T4 is a calculated value from the engine model. The TMF damage model uses engine outputs: P3, T3 (compressor discharge temperature), T4 (turbine inlet temperature), and ITT to calculate the TMF damage of a mission cycle.

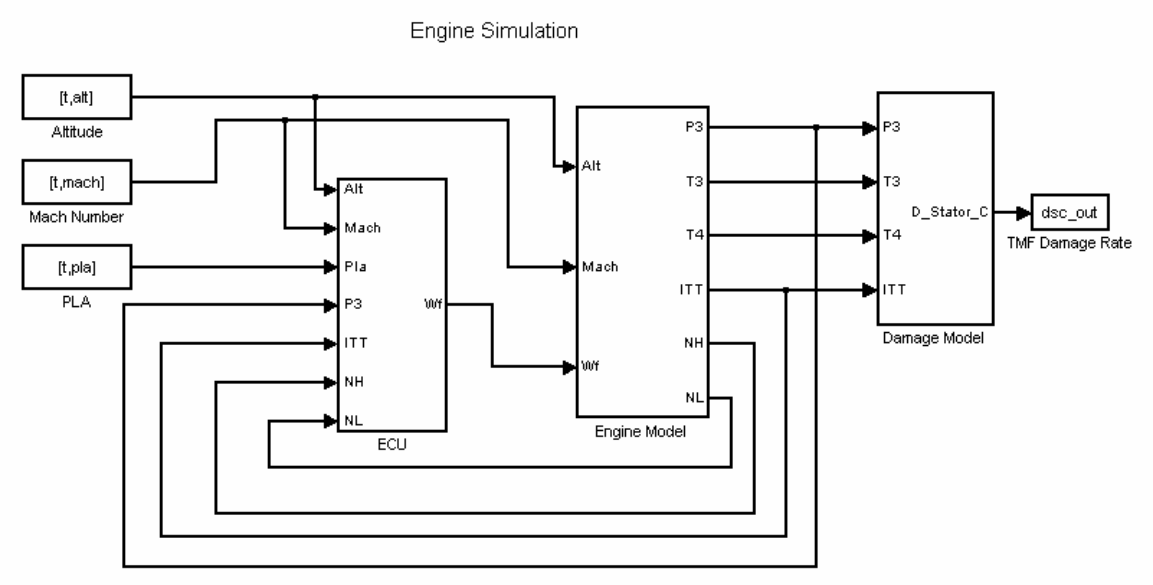

Figure 3. Closed-loop Engine Simulation and Damage Model

Effect of Operating Parameter Variations on Life Usage

This section discusses the series of Monte Carlo simulations performed to study the effects of varying operating conditions on the distribution of life usage. The risk of failure for each scenario was calculated based on the total equivalent life usage. The effects of parameter variations on the eventual risk of failure are discussed. In this study, it is assumed that for each cycle the engine always operates at 100% load with a snap acceleration from ground idle to maximum power within 5 seconds.

1. Standard Operating Conditions

In this case, 5,000 take-offs are simulated under standard conditions (i.e. Altitude=0, and Temperature=59 °F). Since there are inherent uncertainties in the engine system, it is important to capture these variations within the "ideal" take-off condition. These uncertainties include the feedback sensor accuracies, actuator accuracies, and material property variations. All these variations were modeled using normal distributions around the nominal values of the corresponding parameters. The sensor noises assumed here are: 1.5% for P3, 2% for ITT, 0.4% for NH, and 0.4% for NL. The fuel flow actuator also assumes a noise of 0.5%. These values are used in consideration of the dynamic operating condition during the take-off. When these variations were incorporated into the Monte Carlo simulation, the component was found to accumulate more damage than under the ideal conditions. This is due to the highly non-linear nature of the component TMF life model. Since these uncertainties are unavoidable, this case represents the realistic life usage distribution for an engine operated under the defined standard condition.

Figure 4 shows the histogram of normalized effective TMF damage of the component under standard operating conditions. The mean damage of this simulation is calculated to be 1.0742. This is equivalent to a usage of 5,371 cycles under the defined ideal conditions (i.e. when no sensor, actuator, or material uncertainties are present). Using equation (3), the probability of failure is estimated as 0.0133%. Due to the uncertainty of the system, there is a 33% increase in the probability of failure over the previously believed design value of 0.01%.

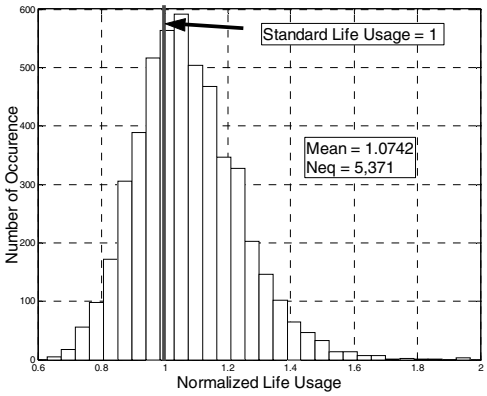

Figure 4. Standard Operation with Engine Uncertainties

2. Typical Variations in Operating Conditions

Aircraft engines will typically operate at a variety of altitudes and ambient temperature conditions during their life-time of use. In this section we will study the effect of these variations. Temperature deviations are included by adding a normally distributed random value with a standard deviation of 30 ºF to the standard ambient temperature. Altitude is randomly distributed between 0 and 1,000 feet. Again, 5,000 take-offs are simulated under these conditions. This is to simulate typical component usage given a more realistic variation in ambient conditions that is likely to be encountered by the engine during its life time of use.

Figure 5 shows the histogram of normalized effective TMF damage given these "typical" variations in ambient operating conditions. (It should be noted that these simulations, also included the feedback sensor inaccuracies, actuator inaccuracies, and material property variations introduced earlier.) The mean damage of this simulation is about 1.1002. This is equivalent to a usage of 5,501 cycles of the defined standard operation. Using equation (3), the probability of failure is estimated as 0.0148%. This increased probability of failure is to be expected for an engine operating under varying ambient temperatures and altitudes. This simulation shows that one can reasonably expect an average of 0.0148% probability of failure for a 5,000 take-off flights instead of the originally believed design value of 0.01%.

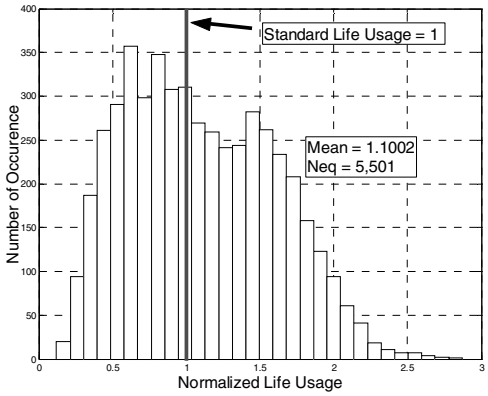

Figure 5. Typical Usage of an Engine

3. Hot Biased Operating Conditions

This study assumes an aircraft engine operates in an area where ambient temperatures are much hotter than the standard conditions on average. In this simulation, a temperature bias of 30 °F with a standard deviation of 20 °F is added to the standard ambient temperature. Altitude is again randomly distributed between 0 and 1,000 feet. The feedback sensor inaccuracies, actuator inaccuracies, and material property variations are also included in this simulation.

Figure 6 shows the histogram of normalized effective TMF damage under these "hot" operating conditions. The mean damage of this simulation is about 1.5783. This is equivalent to a usage of 7,892 cycles of the defined standard condition. Using equation (3), the probability of failure is estimated as 0.062% compared to the original design value of 0.01%. This is more than six times the original design value.

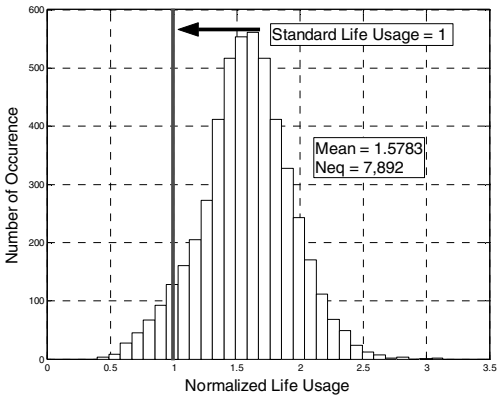

Figure 6. Hot-Biased Operation of an Engine

4. Cold Biased Operating Conditions

This study assumes an aircraft engine operates in an area where ambient temperatures are much colder than the standard conditions on average. In this simulation, a temperature bias of –30 °F with a standard deviation of 20 °F is added to the standard ambient temperature. Altitude is again randomly distributed between 0 and 1,000 feet. The feedback sensor inaccuracies, actuator inaccuracies, and material property variations are also included in this simulation.

Figure 7 shows the histogram of normalized effective TMF damage under these "cold" operating conditions. The mean damage of this simulation is about 0.6344. This is equivalent to a usage of 3,172 cycles of the defined standard condition. Using equation (3), the probability of failure is estimated as 0.00162% compared to the original design value of 0.01%.

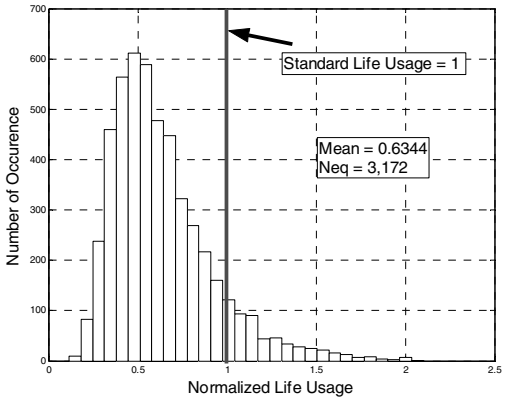

Figure 7. Cold-Biased Operation of an Engine

Comparison

Table 1 shows the comparison of the different study cases. It can be seen that in the "Standard Operation" case, the risk of failure is about 33% higher than the design risk of 5,000 flights due to the uncertainties of sensors, actuators, and material properties. This also represents the more realistic usage profile for given standard ambient conditions. For the "Typical Usage" study case, where varying ambient temperatures and altitudes are considered, the average risk of failure is 48% higher than the design point. In the "Hot-biased" case, the ambient temperatures are consistently higher than the standard condition. The equivalent number of standard flights at 5,000 is actually 7,892. This has a corresponding risk of failure of 0.062%, or 6.2 times of the original value. It is safe to conclude

that an engine component operating at this extreme condition should undergo maintenance much sooner than the nominal 5,000 cycles if the same risk of failure is to be tolerated. On the other hand, in the "Cold-biased" case, much less engine component life is consumed, and the risk of failure at the 5,000 flight point is only a fraction of the original design value. An engine component operated at this condition should be allowed to extend its on-wing service life without any safety concerns.

It should be emphasized that only the TMF failure mode of a cooled stator vane was investigated in this study. The numbers used in this study may not reflect actual engine values; however, the general trend of the damage should still be valid. Also, the general conclusions about component risk of failure should hold.

Conclusions

A component life usage comparison study given different engine operating scenarios is presented. This study uses a commercial engine model and its associated closed-loop controller to simulate engine operation. The thermomechanical fatigue (TMF) failure mode of a cooled stator vane is selected as an example for the study. Life usage is calculated under different operating conditions. The standard operating condition is used as a baseline for comparison. The commonly used 10% rule is used to set the safe life limit for the number of cycles a component can encounter before maintenance must be performed. For this study the component safe life was selected to be 5,000 cycles. A Weibull distribution is then used to estimate the probability of failure at 5,000 cycles of each simulation. Although it is a known fact that the ambient conditions and operating parameters have significant impacts on the engine life, variations in these parameters are not captured in the simplified life usage models typically employed today. This study is an attempt to quantify the impact of uncontrollable uncertainties, as well as the measurable parameters. This study clearly shows the benefit of sensor-based life monitoring in order to avoid the high risk of failure when an engine is operated under severe conditions, or to avoid unnecessary maintenance when the engine is still safe statistically. In this study, it is assumed that the engine always operates at 100% load with a snap acceleration from ground idle to maximum power within 5 seconds.

In future work, this concept can easily be extended to study the effects of actual load variations and acceleration sequence variations during take-offs. Engine component life monitoring using sensor data and on-board model parameters can provide a more accurate estimation of the engine component usage which is essential to both safety and economic engine operations. Accurate estimation of engine component life usage can also be used within life-extending control applications where the engine controller modifies control actions according to the state of component life usage. Such control actions can extend engine component life and assure the safe operation of the engine.

Case	System Parameter Uncertainties	Ambient Temp. Delta	Airport Elevation	5,000 Flight Equivalent	Probability Of Failure @ 5,000
Design Point	None	0	0	5,000	0.01%
Standard Operation	Yes	0	0	5,371	0.0133%
Typical Usage	Yes	Normal S.D.=30	Uniform 0-1,000	5,501	0.0148%
Hot Biased	Yes	Bias=+30 S.D.=20	Uniform 0-1,000	7,892	0.062%
Cold Biased	Yes	Bias=-30 S.D.=20	Uniform 0-1,000	3,172	0.0016%

Table 1. Comparison of Different Engine Operating Assumptions

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13. ABSTRACT ***(Maximum 200 words)***

It is generally known that an engine component will accumulate damage (life usage) during its lifetime of use in a harsh operating environment. The commonly used cycle count for engine component usage monitoring has an inherent range of uncertainty which can be overly costly or potentially less safe from an operational standpoint. With the advance of computer technology, engine operation modeling, and the understanding of damage accumulation physics, it is possible (and desirable) to use the available sensor information to make a more accurate assessment of engine component usage. This paper describes a probabilistic approach to quantify the effects of engine operating parameter uncertainties on the thermomechanical fatigue (TMF) life of a selected engine part. A closed-loop engine simulation with a TMF life model is used to calculate the life consumption of different mission cycles. A Monte Carlo simulation approach is used to generate the statistical life usage profile for different operating assumptions. The probabilities of failure of different operating conditions are compared to illustrate the importance of the engine component life calculation using sensor information. The results of this study clearly show that a sensor-based life cycle calculation can greatly reduce the risk of component failure as well as extend on-wing component life by avoiding unnecessary maintenance actions.

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